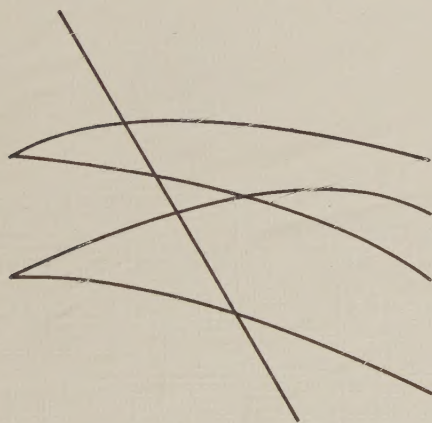


Shell Structure Effects in Nuclei at Very High Spin



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by

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"Everybody makes mistakes,
Everybody makes mistakes,
Even me"

(New Order, 1983)

to Charlotte.

This paper forms an introduction to and a summary of the thesis based on the following papers:

- I T. Bengtsson, Band crossings at very high spins. Progress in particle and nuclear physics, Vol.9, Ed. D. Wilkinson, Pergamon 1983 p.523
- II T. Bengtsson and I. Ragnarsson, Shape changes, band crossings and band terminations in the very high spin region of $A=150-160$ nuclei, Physica Scripta T5 (1983) 165
- III T. Bengtsson, Continuum properties of very high spin states in some rare-earth nuclei. Physics Letters 126B (1983) 411
- IV W. Klamra, J. Bialkowski, L. Hildingsson, D. Jerrestam, A. Johnson, J. Kownacki, Th. Lindblad, J. Nyberg, T. Vertse and T. Bengtsson, Experimental moments of inertia in Pd and Cd isotopes and their interpretation with the extended Nilsson-Strutinsky model, submitted to Nuclear Physics.
- V T. Bengtsson and I. Ragnarsson, Rotational bands and particle-hole excitations at very high spins, submitted to Nuclear Physics.



The average properties of nuclei can be described at a high degree of accuracy if the nucleus is treated as a charged liquid drop [We35,Be36]. The deviation from the values predicted by the liquid drop model are commonly referred to as "shell structure effects", thus representing quantal effects in the nuclear system. An example of a nuclear feature that is attributed to shell structure is the periodic variation of the nuclear mass around the values predicted by a liquid drop model [My66]. Examples of other features that can be explained by shell structure effects are the spin of odd mass nuclei [MN59], the quadrupole moment [Se64] and the mass distribution of fission fragments [Mö70].

Great success in explaining such phenomena as mentioned above has been achieved by employing an average potential as an approximation for the nuclear forces felt by individual nucleons. The Nilsson potential [Ni55], based on the harmonic oscillator is one such average potential. The solutions of the Schrödinger equation gives the possible modes of motion for the individual protons and neutrons in the average potential. These modes of motion are generally called "single particle orbitals".

To properly account for the detailed low-energy properties of nuclei it was found that it was necessary to introduce a "pairing" interaction in the models [BP58]. This pairing interaction resembles to a great extent the superconductivity found in some materials at very low temperatures.

The richness of nuclear structure phenomena became especially apparent when it was found that nuclei show rotational spectra [Hu53,Al56]. The formation of such spectra requires that, the nucleus is deformed, which in itself is a quantal effect. Furthermore, from the relation between energy, E , and the angular momentum (or spin) I in a rotational spectra,

$$E(I) = E(I=0) + \frac{\hbar^2}{2\mathcal{J}} I(I+1) \quad (1)$$

the moment of inertia, $\mathcal{J}$, could be extracted and compared to calculated values. It was then found that nuclei shows a much smaller $\mathcal{J}$ than expected from a rotating rigid body or from the values calculated microscopically from average potentials [BM55]. It was found, that also in this case, the effects of pairing were needed to properly describe the observed values [NP61].

Pairing proved also to be the key factor for an understanding of the nuclear "backbending" phenomenon [Jo72, St76]. This phenomena manifests itself in that suddenly the rotational frequency, ω , of the nucleus as defined by

$$\hbar\omega = \frac{1}{2} [E(I+1) - E(I-1)] \quad (2)$$

decreases as function of the spin I . The backbending phenomenon thus clearly violates equation (1) and gives difficulties in defining the moment of inertia $\mathcal{J}$.

Even though the pairing effects have proven to be very important for the understanding of high-spin spectra, it is widely believed that at sufficiently high spins, the rapid rotation in the nucleus will destroy the pairing correlations. Therefore, much work has been devoted to study the behaviour of nuclei at very high spin in a rotating ("cranked") average potential without pairing [An76, Ne76, Ne77, An78, Åb82]. The cranked potential is obtained by adding a term $-\omega j_x$, to the average potential. The operator j_x refers to the angular momentum along the cranking axis, which is customarily the x-axis and ω the rotational frequency.

In these studies, important changes of the nuclear deformation were predicted as the spin increased. For example, many nuclei are expected to change from being prolate (cigar-) shaped and rotating perpendicular to the symmetry axis, to being oblate (pancake-) shaped with the cranking axis parallel to the symmetry axis. In the latter case, the nucleus is not "rotating as a whole" any longer but instead it builds its spin

from quantum-mechanical particle-hole excitations. At even higher spins, a transition to "superdeformed" shape (ellipsoidal shape with roughly an axis ratio of 2:1) can occur. This should be compared to low spin deformations with a typical axis ratio of $\sqrt{1.3}:1$. Furthermore, predictions about in which nuclear regions rotational behaviour or p-h excitations dominate were later verified by experiment [Pe77]. In spite of the great general value of calculations of the type mentioned above, they can only to a limited degree be helpful in the detailed analysis of very high spin spectra. The main reason for this limitation is the occurrence of crossings and especially so called "virtual crossings" among the single particle orbitals as a function of cranking frequency. A "virtual crossing" means that two single particle orbitals that approach each other in energy as the rotational frequency increases do not cross but instead exchange their character (wave-function) and then move away from each other again. This process introduces severe ambiguities in the final results.

To avoid this problem a method was introduced in ref. [Ra81], which replaced the virtual crossings with real ones, and thus made possible the calculation of the detailed yrast spectra of nuclei. (The yrast state is the state that at a given spin has the lowest energy.) The method presented in ref.[Ra81] was however developed specifically for applications to light nuclei where the number of virtual crossings is small. This thesis describes the application of the method to heavier nuclei. In section 2 of paper V the problem of virtual crossings is therefore given a rather extensive discussion. Further details of the model are also presented there. A part that should be emphasized, as it has proven quite useful in the applications, is the possibility to study specific single-particle configurations. This means that we are able to follow bands outside the region where they are yrast.

The development of the method was essentially finished in 1982. At that time there existed very few experimental data which extended up to the region of spin ($I > 30$) where one could expect that the pairing correlations should be un-

important. Therefore the first application of this method was inspired by observation of enhanced transition probabilities [An82,He83] in a limited region of transition energies in the nucleus ^{166}Yb . Our results were first published in ref. [BR82] and then in somewhat more detail in paper I of the present thesis. The experimental observation could most easily be interpreted as backbends created by the occupation of certain highly aligned orbitals which are predicted to cross the Fermi-surface in just this region of transition energies, where the enhancement was observed.

In paper II, we compare our results with experimentally observed discrete high spin states in the nucleus ^{158}Er [Bu82]. It is found that for the highest spins the transition energies are well reproduced. As we follow this nucleus to even higher spins it starts to change its mode of rotation. So that, around spin 50, it builds its spin mostly from particle-hole excitations. Here, we followed different configurations as they successively approached their termination in states of particle-hole nature. We found that the bands had such properties that they could explain the observation of many M1-transitions [Jä82] (changing the spin with one unit, in contrast to so called "stretched E2"-transitions that changes the spin with 2 units) reported for nearby Yb nuclei. Thus there was evidence that the predicted change from collective rotation to particle-hole excitations mentioned above, could be followed for individual configurations.

Further evidence for shape change was discussed in paper III. In this paper a comparison is made between experimental and calculated values of the number of E2 transitions per energy interval [De80]. The number of transitions is quantified by the so called effective moment of inertia $\mathcal{J}_{\text{eff}}^{(2)}$, which measures how much angular momentum is created in a specific energy interval. (In section 3 and 6.2 of paper V different definitions of $\mathcal{J}$ are presented.) It was found that a strong increase of $\mathcal{J}_{\text{eff}}^{(2)}$ at high rotational frequencies in ^{166}Yb , could be explained by a sharp backbend caused by the transition to superdeformed shape mentioned above. In contrast, ^{160}Er , which

did not show any significant increase, is not predicted to attain a superdeformed shape before it has reached frequencies that are outside experimental limits. The general agreement between experimental and calculated values of $\bar{\sigma}_{\text{band}}^{(2)}$ thus indicates that superdeformed shapes are observed in $^{166}_{\text{Yb}}$.

Another interesting quantity that can be obtained from unresolved transition energies is the moment of inertia within a specific band, $\bar{\sigma}_{\text{band}}^{(2)}$. A presentation of experiments performed to obtain this quantity in ^{106}Pd and a few of its neighbouring nuclei is given in paper IV. Values of $\bar{\sigma}_{\text{band}}^{(2)}$ up to very high rotational frequencies (0.9 MeV) are extracted and found to show some interesting variations. The calculations presented in paper IV show that our method is able to properly describe the average value of the measured $\bar{\sigma}_{\text{band}}^{(2)}$. Furthermore as a possible explanation for the variations, it was found that they could be caused by shape changes in the rotational bands approaching termination.

We come now to the last and largest paper included in this thesis, paper V, which contains the essential parts of the theory and a wide range of applications. In addition to applications to quasicontinuum experiments, similar to those mentioned above, also comparisons between calculated and experimental resolved high spin states for a few nuclei are presented. For these nuclei, it is found that transition energies are in general well reproduced above a spin of about 30 $\hbar$. This observation is thus in accordance with the assumption that pairing should be more or less unimportant at these very high spins. The remaining discrepancies can mainly be put into two categories, those that probably are due to the fact that the average potential used does not exactly reproduce the shell structure in real nuclei and those that can be attributed to effects that resemble pairing. In the first case, further studies are needed to find an improved average potential. In the latter case, one might be able to study the onset of pairing by starting from an unpaired nuclear system at very high spin. It thus seems that by studying the properties of nuclei in the extreme situation when they rotate very rapidly,

there is hope to get a better understanding of nuclear ground-state and low-spin properties.

Finally, I wish to express my gratitude to Ingemar Ragnarsson in particular and the whole department of Mathematical Physics in general, for a fruitful cooperation over the period of many years. Thanks are also due to my non-human aide, the LUCAS-CAESAR computer, for keeping track of the bits and bytes of the entire thesis.

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